Very Long Baseline Neutrino Oscillations

Milind Diwan
Brookhaven national Laboratory
Annual DOE program review, April 2005

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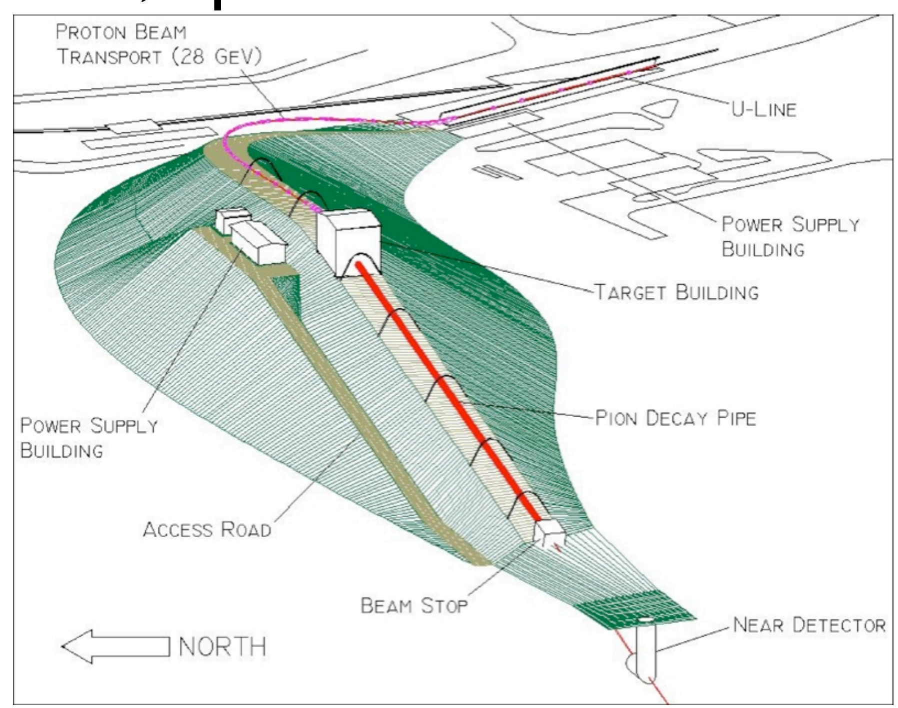
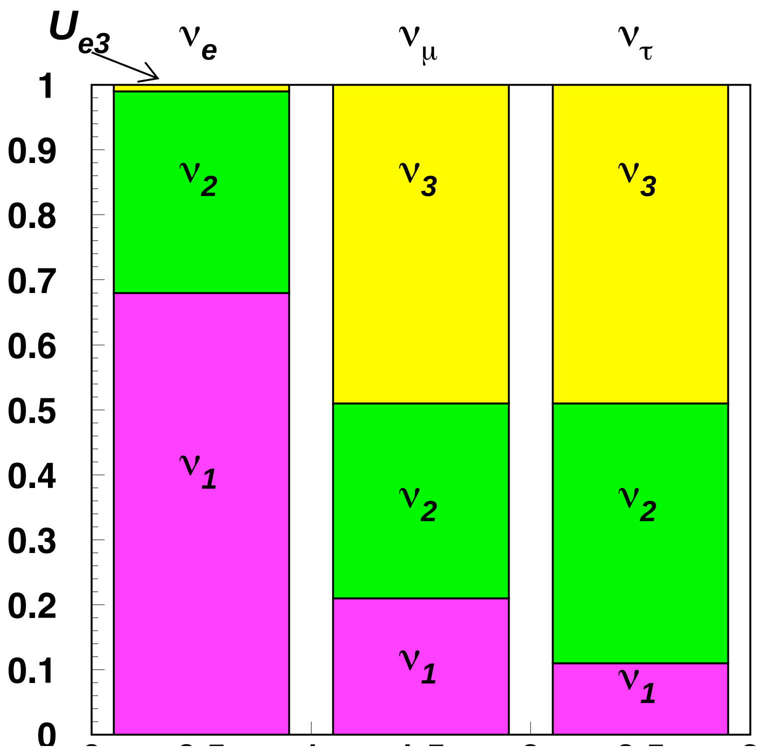
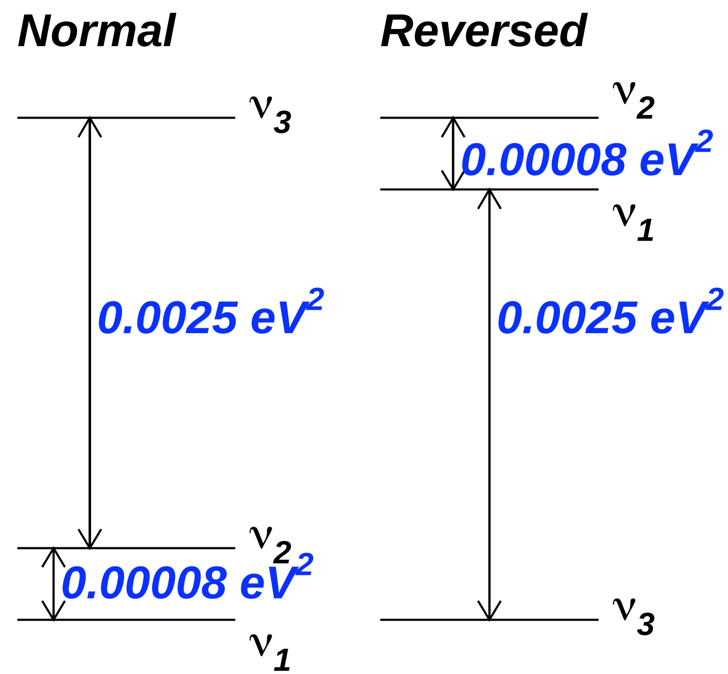


3 Generation oscillations





Difference in mass squares: $(m_2^2 - m_1^2)$

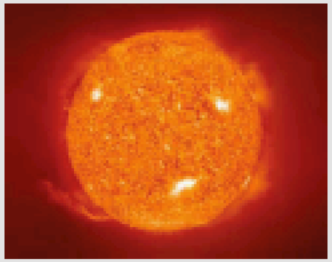
2-nu: $$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

3-nu:
$$\begin{aligned}
P(\nu_a \rightarrow \nu_b) \quad = \quad & \textstyle\sum_i |U_{ai}|^2 |U_{bi}|^2 \\
& + 2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E) \\
& + 2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E) \\
& + 2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2 L/2E)
\end{aligned}$$

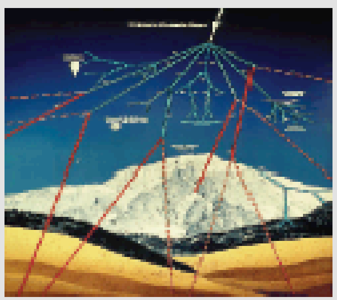
no matter effects

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1 GeV$, $L = 494 km$.

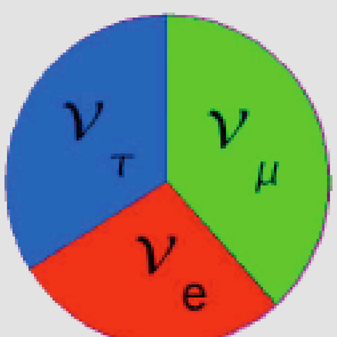
Neutrino Oscillations Results



$$\Delta m^2_{21} = (8.0 \pm 0.3)\, 10^{-5}\, eV^2$$
$$\sin^2 2\theta_{12} = 0.86 \pm 0.04$$



$$|\Delta m^2_{32}| = (2.5 \pm 0.3)\, 10^{-3}\, eV^2$$ sign?
$$\sin^2 2\theta_{23} = 1.02 \pm 0.04$$ degeneracy?



$$\sin^2 2\theta_{13} < 0.12$$ (99% C.L.)
$$\delta_{CP} = ???$$

Values from: A. Strumia & F Vissani
hep-ph/0503246 - ifup-th/2005-06

Next Generation Experiments

- increase sensitivity $\sin^2 2\theta_{13}$ & δ_{CP} significantly
- precision measurements of Δm^2_{32} & $\sin^2 2\theta_{23}$
- resolve mass hierarchy (sign of Δm^2_{32})
- sensitive to new physics

To go to the heart of the 3 generation picture must have experiment with L/E that includes effects from both mass differences.

- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector.
- baseline > 2500 km. WIPP, Henderson, Homestake

Working group chronology

- December, 2001: Tom Kirk gave us a charge to form a working group.
- ~50 Members from Physics department, CAD, and outside universities.
    - Coordinators: W. Marciano (physics), M.Diwan(simulations), W.Weng(accelerator upgrade)
- BNL HENP PAC (2002)
- Internal AGS review (June 2004)
- HEPAP facilities plan(2003), Absolutely central.
- APS neutrino study (2004)
- NESS workshop(Sep 2002), DUSEL S1 and S2 workshops, 3 BNL/UCLA workshops(Dec 2003, May 2004, Feb 2005)

Working group written material

W. J. Marciano, "Long baseline neutrino oscillations and leptonic CP violation," Nucl. Phys. Proc. Suppl. **138**, 370 (2005).

M. V. Diwan, "The case for a super neutrino beam," Heavy Quarks and Leptons Workshop 2004, San Juan, Puerto Rico, 1-5 Jun 2004. arXiv:hep-ex/0407047.

J. Alessi, et al., "The AGS-based Super Neutrino Beam Facility, Conceptual Design Report," BNL-73210-2004-IR, 1 Oct. 2004.

W. T. Weng *et al.*, J. Phys. G **29**, 1735 (2003).

W. J. Marciano, "Extra long baseline neutrino oscillations and CP violation," BNL-HET-01-31, Aug 2001. 11pp. arXiv:hep-ph/0108181.

M. V. Diwan *et al.*, "Very long baseline neutrino oscillation experiments for precise measurements of mixing parameters and CP violating effects," Phys. Rev. D **68**, 012002 (2003) [arXiv:hep-ph/0303081].

R, May 2003. 114pp.

)02. 100pp.

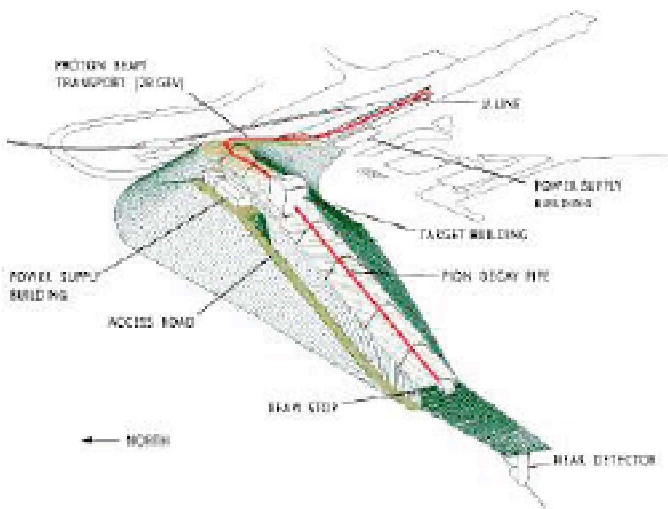
ılar multi-purpose neutrino detector for a program of physics in the Homestake DUSEL," arXiv:hep-ex/0306053.

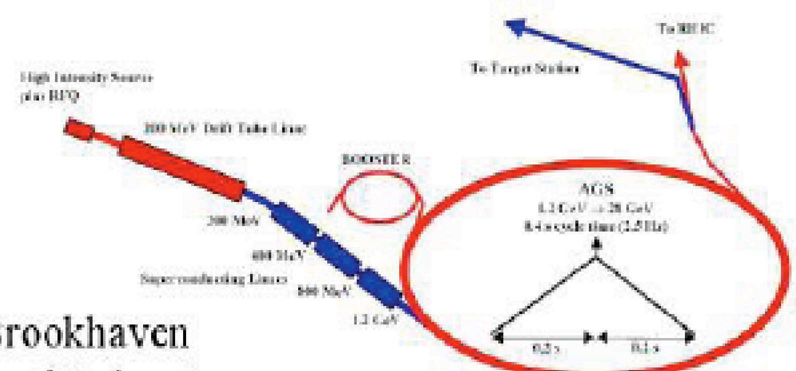
We are after the science and facilities absolutely central to the US HEP program: Neutrino super beam and a large capable underground detector.

AGS Conceptual Design Report

BNL-73210-2004-IR

The AGS-Based Super Neutrino Beam Facility
Conceptual Design Report





Brookhaven
National Laboratory
Upton, NY 11973
8 October 2004

October 8, 2004 BNL-73210-2004-IR

The AGS-Based Super Neutrino Beam Facility
Conceptual Design Report

Editors: W. T. Weng, M. Diwan, and D. Raparia

Sent to DOE Oct 2004

Contributors and Participants

I. Alessi, D. Barton, D. Beavis, S. Bellavia, I. Ben-Zvi, J. Brennan, M. Diwan, P. K. Feng, J. Gallardo, D. Gassner, R. Hahn, D. Hseuh, S.Kahn, H. Kirk, Y. Y. Lee, E. Lessard, D. Lowenstein, H. Ludewig, K. Mirabella, W. Marciano, I. Marneris, T. Nehring, C. Pearson, A. Pendzick, P. Pile, D. Raparia, T. Roser, A. Ruggiero, N. P. Samios, N. Simos, J. Sandberg, N. Tsoupas, J. Tuozzolo, B. Viren, J. Beebe-Wang, J. Wei, W. T. Weng, N. Williams, P. Yamin, K. C. Wu, A. Zaltsman, S. Y. Zhang, Wu Zhang

BNL-73210-2004-IR

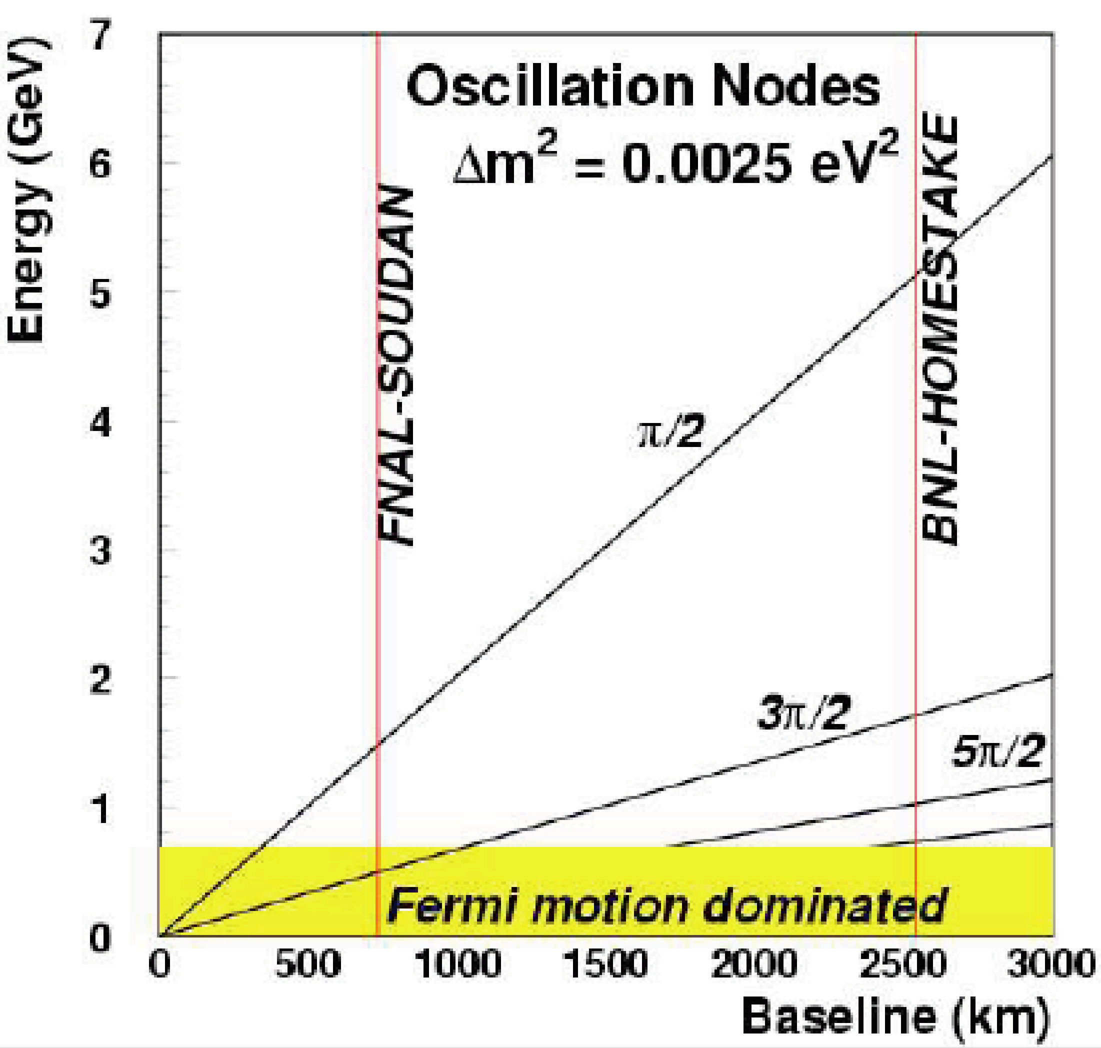
Brookhaven National Laboratory
Upton, NY 11973
October 8, 2004

http://raparia.sns.bnl.gov/nwg_ad/agsnbcdr1.pdf

Why Very Long Baseline?

observe multiple nodes in oscillation pattern

☞ less dependent on flux normalization



neutrino travels larger distance through earth

☞ larger matter effects

flux ~ L^{-2}: lower statistics

but: CP asymmetry ~ L

☞ sensitivity to δ_{CP} independent of distance!

better S:B

(Marciano hep-ph/0108181)

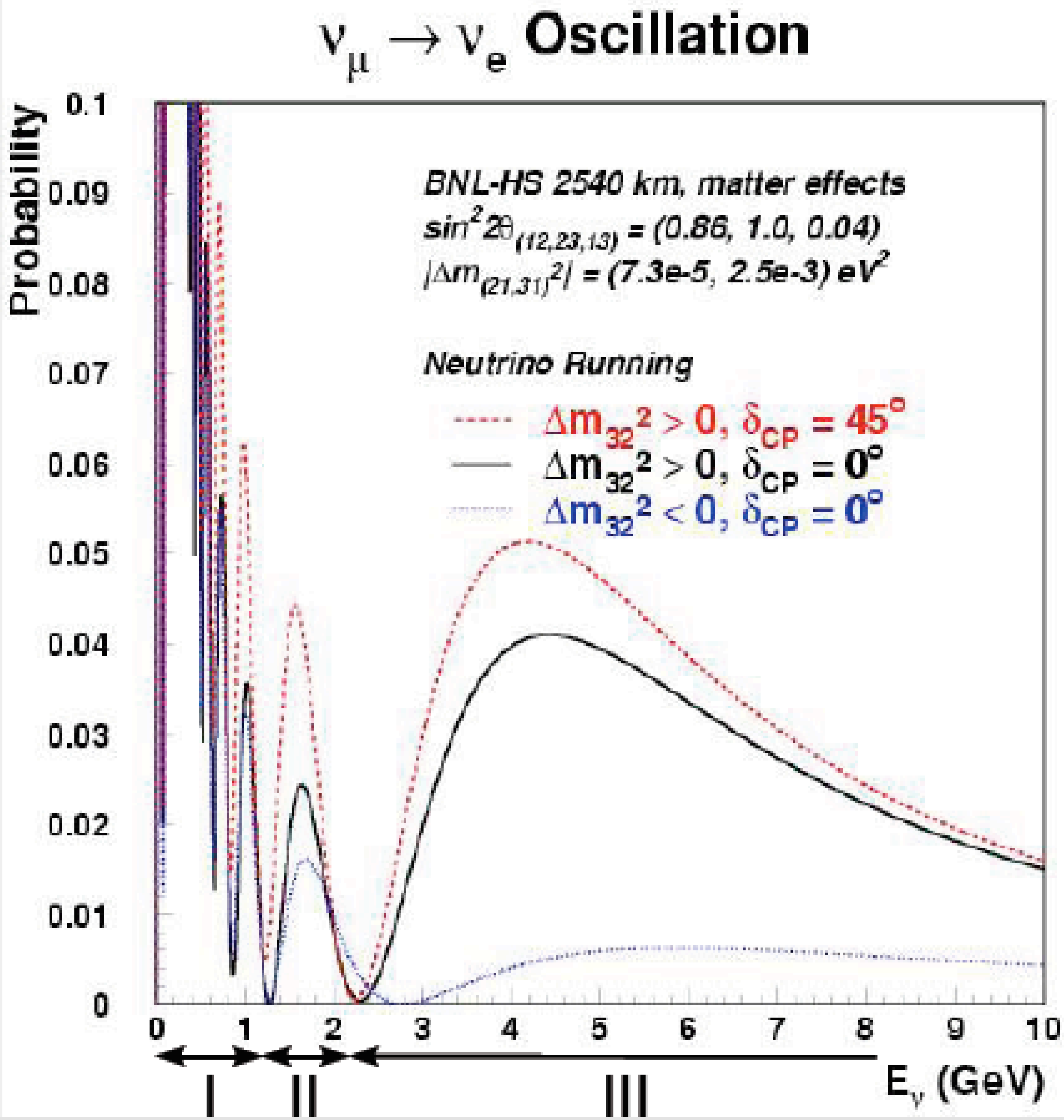
Why Broadband Beam?

observe multiple nodes

larger energies
☞ larger cross sections

Sensitive to different parameters in different energy regions:

	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
sign(Δm^2_{32})	0	0	++
δ_{CP}	+	++	+
solar	++	+	+

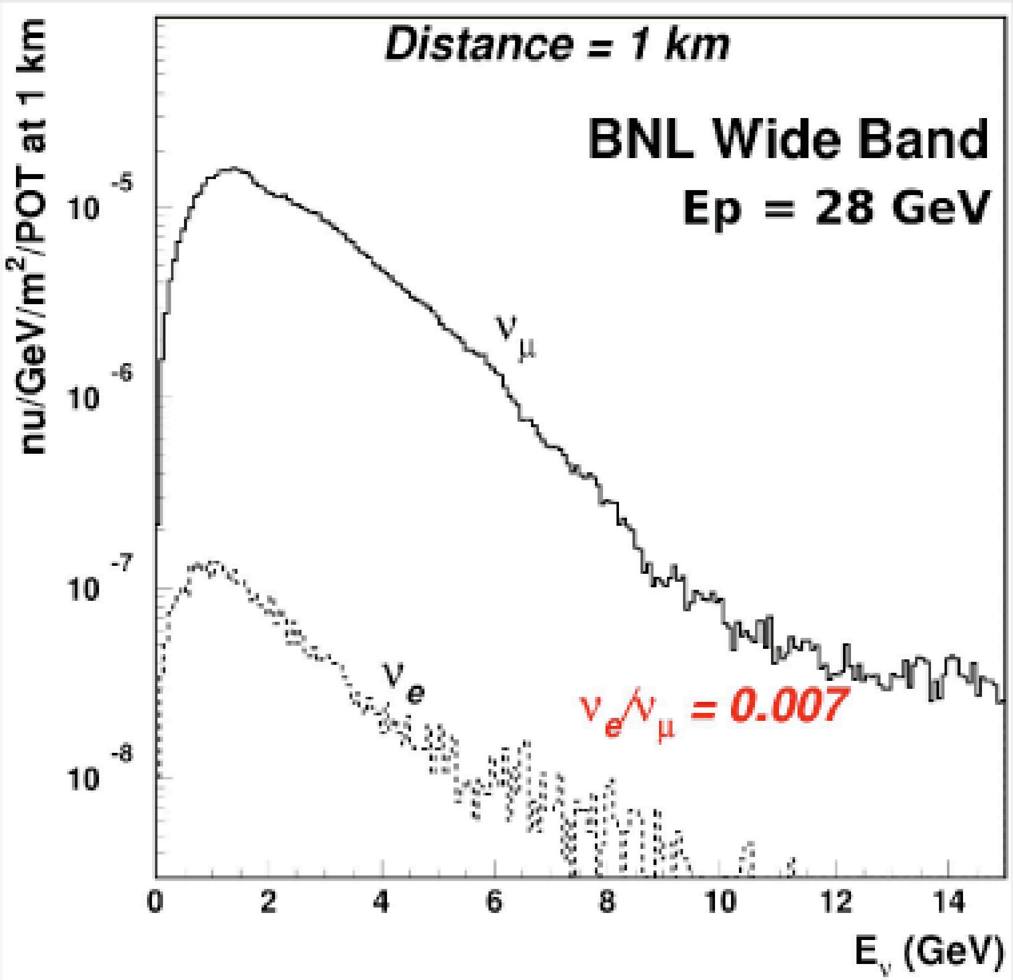


AGS 1MW proton beam

Upgrade AGS (28 GeV protons)

intensity: $7.10^{13} \rightarrow 9.10^{13}$ ppp

rep. rate: 0.5Hz → 2.5Hz



1) ramp time: 0.5s → 0.2s

repl. power supply, rf, ...

2) filling time: 0.6s → 1ms

replace booster:

exist. warm linac 200 MeV

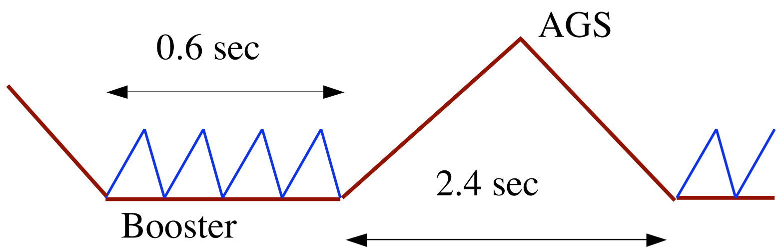
new SC linac 1 GeV

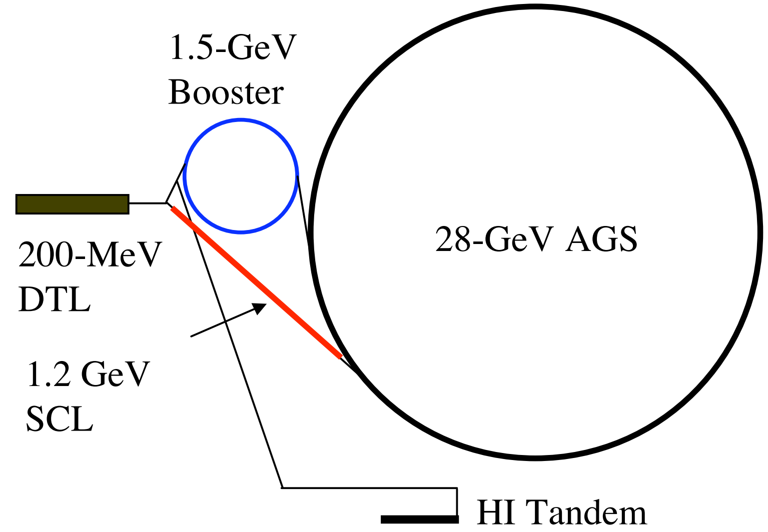
cost estimate: $273M

(excl. contingency)

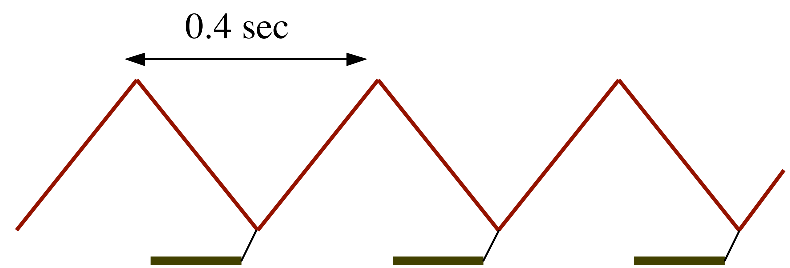
takes 6 years to complete

Two Injection Schemes

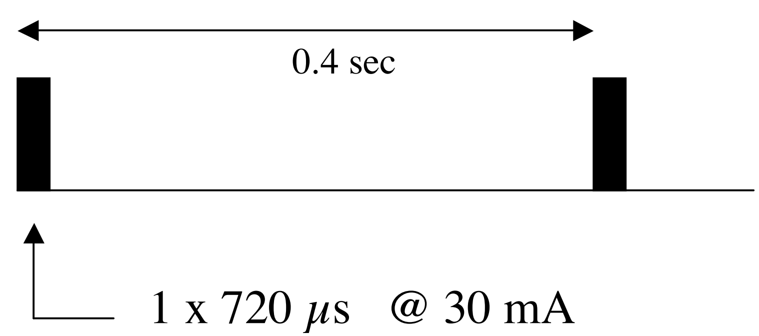




	AGS present	AGS upgrade
Kin. Energy	28 GeV	28 GeV
Rep. Rate	1 / 3 Hz	2.5 Hz
Protons/ Cycle	0.67 x 10^{14}	0.89 x 10^{14}
Ave. Power	0.10 MW	1.0 MW



Typical DTL cycle for Protons



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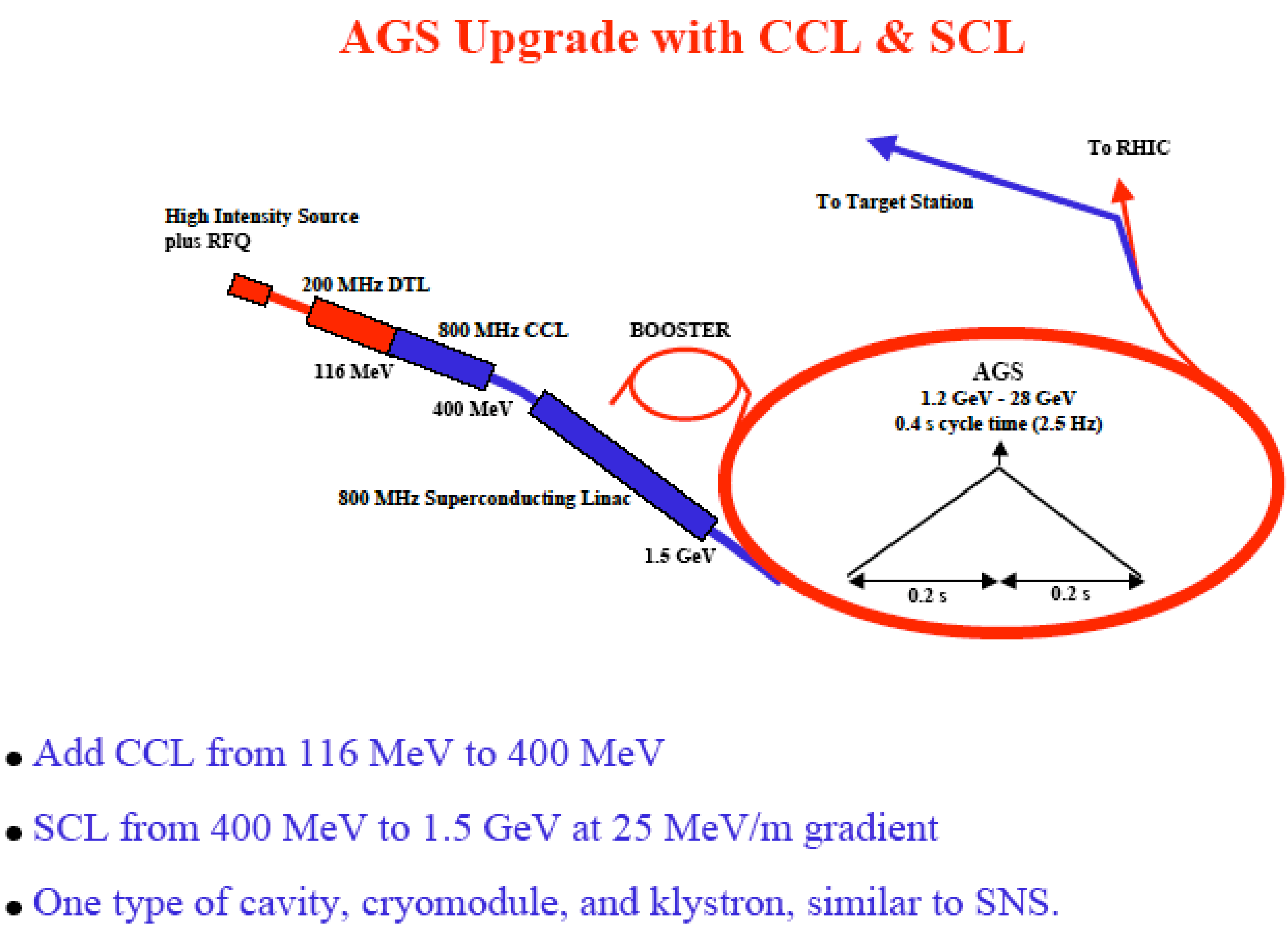
Status of technical progress on AGS



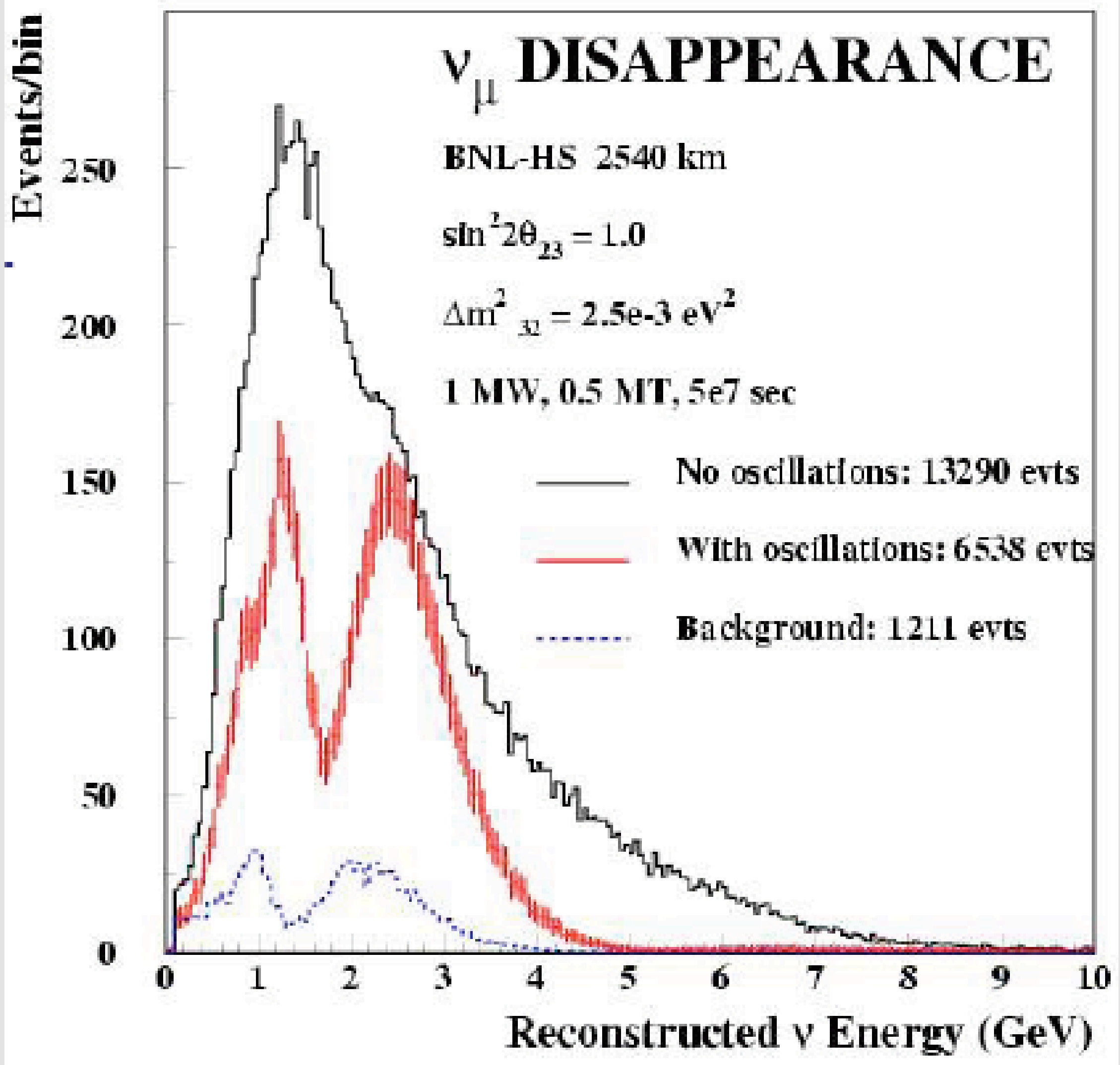
- New design for LINAC could bring us to 1.5 MW
- Experimental work on carbon-carbon target irradiation yielding results.

ν_μ disappearance

neutrino running:

1MW beam
0.5Mt water Cerenkov det.
2540km distance
5e7s running time

determine Δm^2_{32}
& $\sin^2 2\theta_{23}$ to 1%
systematics dominated



anti-neutrino running:

same as ν but with
2MW beam

including anti-ν running:
- CPT test possible
- errors below 1% achievable

ν_e Appearance

<u>backgrounds:</u>

- beam ν_e
- NC ν_μ

<u>neutrino running:</u>

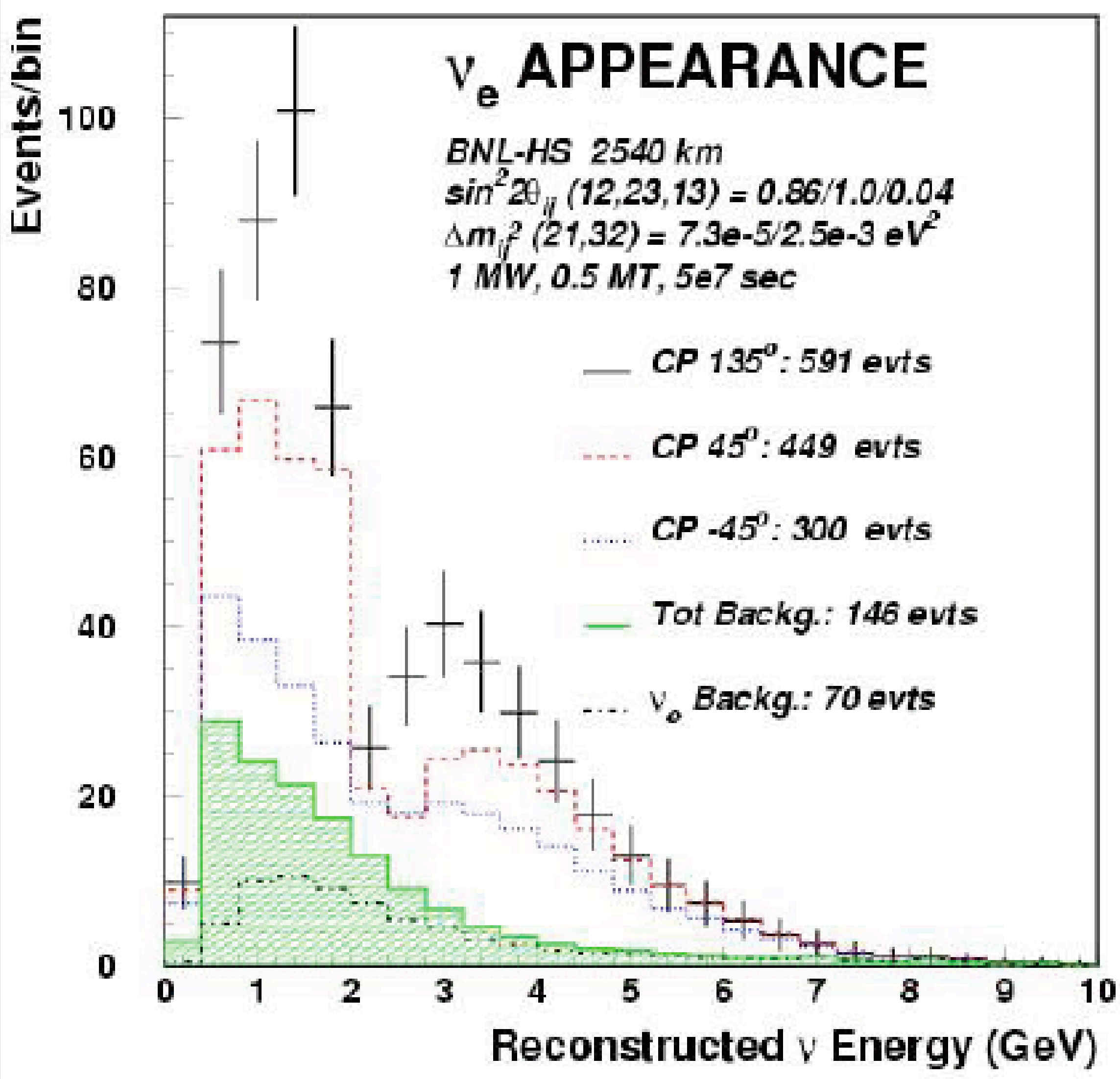
measure $\sin^2 2\theta_{13}$ and δ_{CP}

for $\sin^2 2\theta_{13} > 0.01$

resolve mass hierarchy

<u>include anti-neutrino run:</u>

exclude $\sin^2 2\theta_{13} > 0.003$



if $\sin^2 2\theta_{13}$ too small → δ_{CP} measurement not possible

observation ν_e appearance possible through solar term

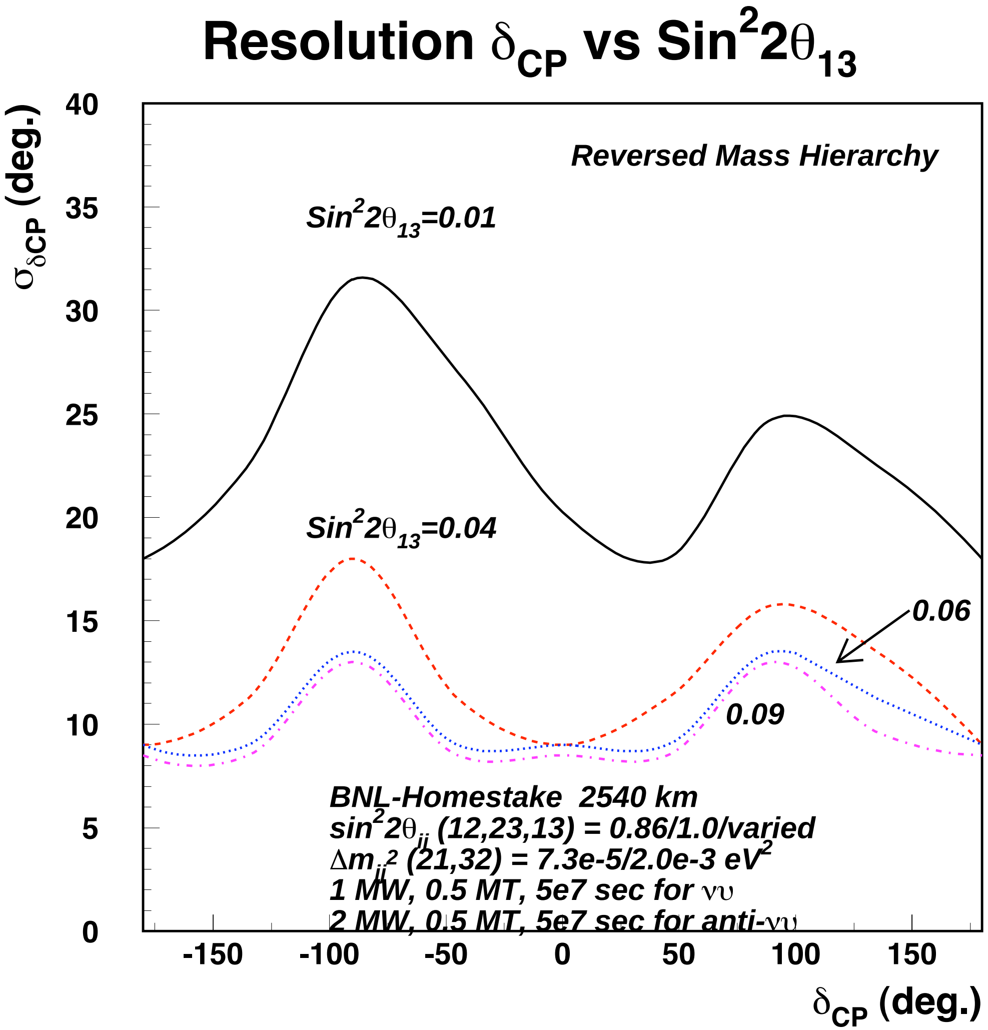
Status of physics work

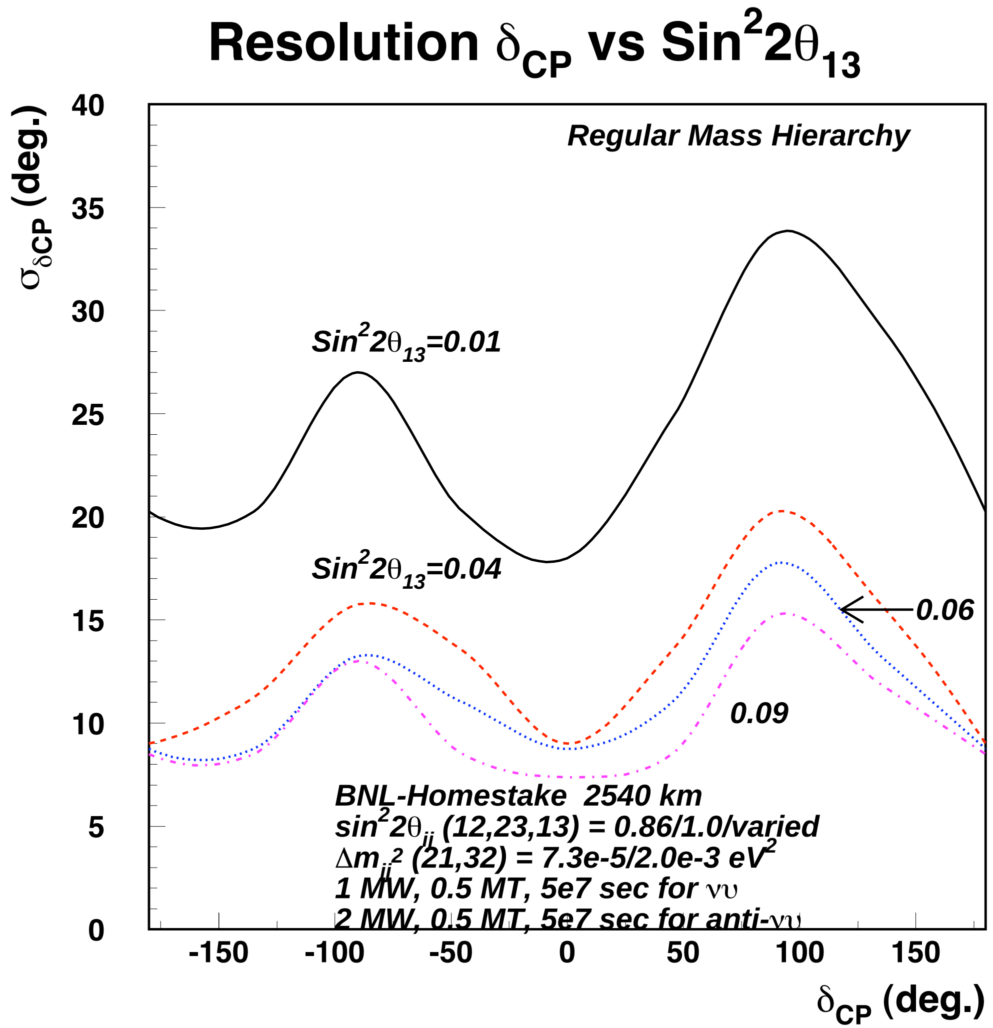
- Have examined physics reach with anti-neutrino running.
- Have examined more detailed issues regarding baseline. Optimization based on physics judgement. But longer baseline => better science.

M. Diwan, Proc. Heavy Quarks and Leptons, hep-ex/0407047

- GREAT PROGRESS ON DETECTOR BACKGROUNDS !

CP resolution





More than 10 sigma resolution of mass hierarchy after anti-neutrino running and excellent resolution on delta-CP.

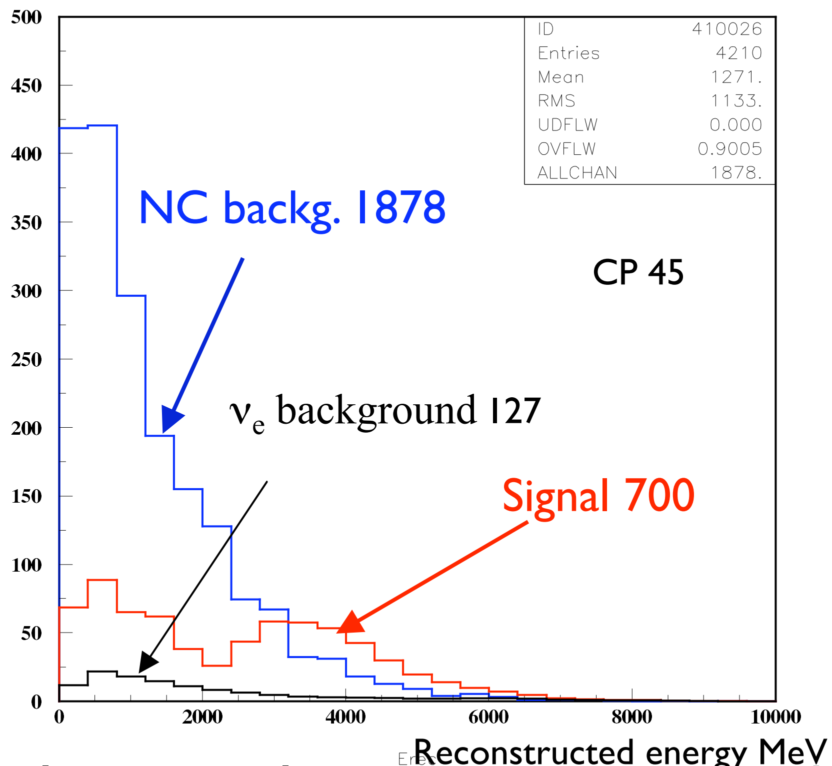
Detector

- 500 kT fiducial mass for both proton decay and neutrino astro-physics and neutrino beam physics.
- ~10% energy resolution on quasielastic events.
- muon/electron separation at <1%
    - 1,2,3 track event separation.
    - Showering NC event rejection at factor of ~20.
- Low threshold (~5 MeV) for solar and supernova physics.
- Time resolution ~few ns for pattern recognition and background rejection.

Complete water Cherenkov detector simulations progress

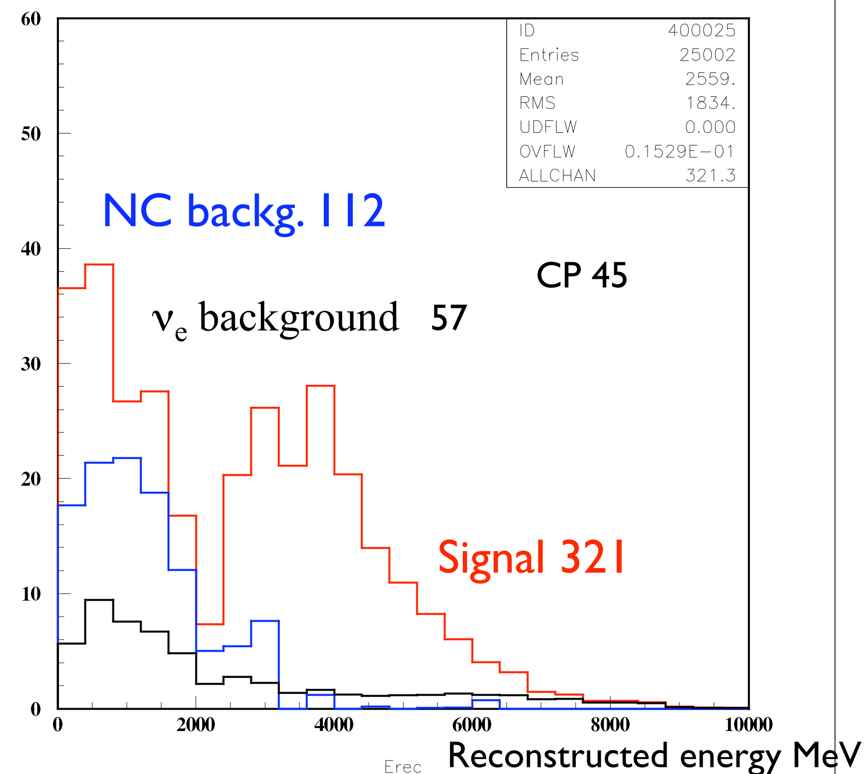
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

- $\Delta m^2_{21} = 7.3 \times 10^{-5}\ eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$
- $\sin^2 2\theta_{ij}(12,23,13) = 0.86/1.0/0.04$, $\delta_{CP} = +45, +135, -45, -135^o$



Select single ring events and select electrons

Signal/backg = 700/2005



Perform analysis of single electron pattern, cut likelihood retaining ~50% of signal.

Signal/back = 321/169

C. Yanagisawa (Stony Brook), 3rd BNL/UCLA workshop
http://www.physics.ucla.edu/hep/proton/proton2005.htm

Signal/background

_ S/B

No magic. Performance is obtained by giving up large fraction of potential signal CC events; and using the kinematics of NC events.

Summary of BNL superbeam@UNO

Preliminary

CP phase	Signal	Bkg	Effic	Signal	Bkg	Beam ν_e
0°	ν_e CC	ν_μ all, ν_e NC	40%	178	75	43
-135°	ν_e CC	ν_μ all, ν_e NC	40%	233	78	44
+135°	ν_e CC	ν_μ all, ν_e NC	40%	342	81	45
-45°	ν_e CC	ν_μ all, ν_e NC	40%	142	75	43
+45°	ν_e CC	ν_μ all, ν_e NC	100%	700	1878	127
			50%	321	112	57
			40%	251	74	44

with traditional water Chrenkov cuts

Chiaki Yanagisawa

Scientific Reach of Future Neutrino Oscillations Exps.

Parameter	T2K	T2HK	Reactor	Nova	Nova2	VLBNO
Δm_{32}^2	✓	✓	-	✓	✓	✓
$\sin^2(2\theta_{23})$	✓	✓	-	✓	✓	✓
$\sin^2(2\theta_{13})$ [a]	✓	✓	✓	✓	✓	✓
$\Delta m_{21}^2 \sin(2\theta_{12})$ [b]	-	-	-	-	-	12%
sign of (Δm_{32}^2) [c]	Nova	-	-	T2K	T2K	yes
measure δ_{CP} [d]	-	Nova	-	-	T2HK	±13°
N-decay improv.	x1	x20	-	-	-	x10
Detector (KTons)	50	1000	20	30	30	400
Beam Power (MW)	0.74	4.0	14000	0.65	2.0	1.5
Baseline (km)	295 [e]	295 [e]	1	810 [e]	810 [e]	>2500
Detector Cost ($M)	exists	~$$$	20	165	+ ???	$$
Beam Cost ($M)	exists	$$	exists	$	$$$	400

Combined measurement

[a] detection of $\nu_\mu \rightarrow \nu_e$, upper limit on or determination of $\sin^2(2\theta_{13})$

[b] detection of $\nu_\mu \rightarrow \nu_e$ appearance, even if $\sin^2(2\theta_{13}) = 0$; determine θ_{23} angle ambiguity

[c] detection of the matter enhancement effect over the entire δ_{CP} angle range

[d] measure the CP-violation phase δ_{CP} in the lepton sector; Nova2 depends on T2HK

[e] beam is 'off-axis' from 0-degree target direction

Comments on Neutrino Oscillations Experiments

• *All* parameters of neutrino oscillation can be measured in <u>*one*</u> experiment

- a Very Long Baseline Neutrino Oscillation (VLBNO) at >2000 km
- the cost of VLBNO is comparable to (or less than) competing proposals
- the mass of the VLBNO target enables a powerful *Nucleon Decay* search

• Use of a *broadband neutrino beam* at *very long distances* is the key

• Focus on CP because **The CP-violation parameter is the most difficult parameter to determine**

- matter effects interact with CP-violation effects
- the CP-violation phase δ_{CP} has distinct effects over the full 360° range

• **Off-axis beam method requires multiple distances and detectors**

- all experiments will require of order 10 Snomass years of running

• **All measured oscillation parameters will be limited to ~1% precision by systematic errors except $\sin^2(2\theta_{23})$**

Wanted

- Resources to lower costs of the AGS upgrade and super neutrino beam.
- Must push 1 MW target studies to completion.
- Resources to push water Cherenkov simulations as well as start detector R&D.
- University groups need to consider this part of the their future.

Conclusions

- Powerful new method for neutrino CP violation study. Absolutely central part of the HEP facilities plan and the APS neutrino study plan.
- We have made great progress on many technical issues.
- Important work performed on detector background issue.
- Need patience, encouragement, and resources to make a proposal.
- EXPECT A DETECTOR R&D PROPOSAL SOON.